Building and Environment 144 (2018) 611–621

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

An operational methodology for applying dynamic Life Cycle Assessment to buildings

Koji Negishi[a,b], Ligia Tiruta-Barna[a,*], Nicoleta Schiopu[b], Alexandra Lebert[b], Jacques Chevalier[b]

[a] LISBP, Université de Toulouse, CNRS, INRA, INSA, Toulouse, France, 135 Avenue de Rangueil, 31077, Toulouse, France
[b] Centre Scientifique et Technique du Bâtiment, 38400, Saint-Martin-d'Hères, France

ARTICLE INFO

Keywords:
Building
Dynamic life cycle inventory
Dynamic life cycle impact assessment

ABSTRACT

While the Life Cycle Assessment (LCA) method is a powerful tool for environmental performance evaluation, the current LCA methodology faces some limitations in evaluating environmental performances of systems with a long time scales, such as buildings. Building systems have particularly long lifetimes as compared to other products or services. They are composed of elements that evolve over time and are characterized by time-dependent parameters. A literature review was performed in the aim of identifying the time-dependent characteristics of a building system at different levels: building technology level (e.g. technical performance degradations and technological innovations), end-user level (e.g. occupant behaviour) and external system level (e.g. infrastructures, energy mix, regulations). A new LCA framework including the time dimension, applied to a building system, is proposed. It involves operational and reproducible tools (computational software and databases) to perform effective temporal evaluations and incorporates dynamic Life Cycle Inventory (LCI, including the temporal evolution of a building system and of the related environment interventions, i.e. emissions and resource consumption) and dynamic Life Cycle Impact Assessment (LCIA, climate change and toxicity). To integrate the specificities of buildings in dynamic LCI modelling, different existing assets (at national and international level) in the field of LCA are analysed. This work proposes an original methodology for performing a dynamic LCA of buildings using new tools still under development.

1. Introduction

Life Cycle Assessment (LCA) has become an indispensable method for quantifying the environmental performance of products or services and is widely used in many sectors of activity. Environmental issues of buildings concerning both energy and embodied materials have increasingly been acknowledged by several scholars, who have illustrated their methodological developments for environmental assessment of buildings through case studies [1–3]. Different types of building structures, scenarios of replacement and refurbishment phases, construction products, and end-user energy consumption have been compared in terms of their environmental performance. Moreover, some studies have focused on energy use throughout the building lifetime, investigating how to estimate orders of magnitude of energy uses from the construction to demolition of the building [4,5]. The considerable amount of waste resulting from the construction activity and the dismantling of buildings has led us to consider demolition waste recycling. While building-LCA studies have seen methodological improvements integrating more and more complex elements of the building system, the evolution of that system over its life cycle has remained beyond the scope of studies, as buildings have particularly long lifetimes compared to other products or services. Building systems are composed of elements that evolve in time and are characterized by time-dependent parameters. At the technological level related to the building sector, the degradation of technical performances of buildings may be one of the key dynamic parameters. On the other hand, energy consumption varies with time and its variation is determined by technological parameters, occupant behaviour, energy equipment characteristics and climate conditions. Another aspect influencing energy consumption by a building system is the economic and environmental context. The evolution of policy rules, e.g. national energy strategies and environmental regulations, may encourage the construction sector to reduce material and energy use and can stimulate a reduction of related environmental impacts e.g. near zero energy and low carbon footprint buildings: the "E + C- approach", a large-scale experiment aiming to prepare a new environmental building regulation in France [6]. The European project "Levels" is also based on the concept of applying a life-cycle approach to building design [7,8]. Therefore, decisions for

* Corresponding author. INSA Toulouse, LISBP, 135 Av de Rangueil, F-31077, Toulouse, France.
E-mail address: ligia.barna@insa-toulouse.fr (L. Tiruta-Barna).

https://doi.org/10.1016/j.buildenv.2018.09.005
Received 21 June 2018; Received in revised form 16 August 2018; Accepted 4 September 2018
Available online 05 September 2018
0360-1323/ © 2018 Elsevier Ltd. All rights reserved.

construction materials, maintenance, replacements, and refurbishment, together with scenarios of the end of life, should be placed in the context of national and European regulations that change over time depending on the energy, environmental and economic background. The electricity production mix and, more generally, the energy resources used vary over time with regard to the availability of energy resources, the economic situation of a country, climate and agriculture for renewable energy development, etc. Some of these dynamic parameters considerably impact LCA results for buildings.

Many environmental standards currently exist in the field, at national levels as well as in Europe. For example, the European standard EN 15978 on the assessment of the environmental performance of buildings is applicable to new and existing buildings, and refurbishment projects [9]. These standards give the rules for quantitatively evaluating the environmental performance of buildings based on the life cycle approach. Different life cycle-based tools complying with these rules or environmental regulations have been developed to help design sustainable buildings with respect to country-specific contexts, e.g. ELODIE in France [10]. The specificities of some existing building-LCA tools will be mentioned in the following sections. Even though efforts are being made on the development of LCA tools along with efforts to regularly upload environmental data, none of these tools allow the temporal dimension to be considered, either at the level of material and energy balance, or at the level of environmental impact calculations. Actually, there are no tools (methods, norms, or databases) enabling temporal characteristics to be taken into account that are explicit and specific to buildings. Nevertheless, prospective evaluations can be performed by using specific energy and material balances averaged over given time periods.

In this context, the need for a more realistic evaluation of the environmental performances over long time frames leads us to consider a dynamic LCA approach adapted and completed for application to the building sector. Thus, the general goal of this work is to propose a methodology for considering time in LCA of buildings. In order to reach our goal, the present paper (i) aims to identify the main temporal aspects of a building system (section 2), (ii) analyses the literature related to the dynamic LCA assessment in the field of buildings, and (iii) proposes a framework for temporal LCA applied to buildings. Key dynamic parameters of the building system, the method of dynamic inventory data, calculation tools, expected results and also the main limitations of the proposed general framework are presented.

2. Time-dependent factors and parameters of a building system

Before analysing the temporal aspect in LCA applied to buildings, this section will present the temporal variation of building systems encountered from a variety of aspects.

Energy consumption varies from hour to hour, day to day, week to week, season to season, and year to year, depending on various factors. The typology of inhabitants and their behaviour are variable depending on the economy, culture, and climate, and play an important role in determining the energy consumption level and its temporal behaviour. From a literature review, de Meester et al. [11] selected the three parameters having most influence on the heating loads in a single-family house: 1) type of occupancy (e.g. family size, age), 2) management of thermal comfort (e.g. temperature set point, functioning time of energy systems) and 3) area heated. They created 7 levels of thermal performance for the house (from zero insulation to standard level insulation for a passive house). Each scenario uses different insulation materials in the wall, floors, and roof. If the insulation level is low, the heat load management (temperature specification and heating time) becomes important to reduce energy consumption. On the other hand, when the house is well insulated, the type of occupancy greatly impacts the energy consumption level. Four scenarios of occupancy over 100 years, combining the above three parameters, were evaluated in terms of heating loads, and the maximal difference between scenarios reached 26%. As evoked in their discussion, in a long time scale analysis, the house should be adapted to the evolution of the family, including possible improvements in thermal insulation.

Technical performances related to construction products and energy equipment degrade over the long lifetime of buildings. Insulation materials deteriorate over time due to climate conditions (e.g. humidity) and the occupant needs to replace such building materials in order to maintain the thermal comfort. Studies exist on how the degradation of building components (especially insulation materials) occurs over time, affecting the energy consumption [12–14]. One of these research works examined the durability of insulation materials in terms of their thermal-hygrometric and mechanical performances, showing a 12% increase in thermal conductivity over 25 years. The effects of such degradations on the energy performance of buildings was observed and simulated over time for different envelope structures e.g. exterior walls, floors, and roof. Marceau et al. [15] showed that bio-based insulation materials, such as wood wool are particularly sensitive to climate conditions, and their thermal performance can deteriorate due to the variation of water content in the products. Degradations of technical performance will lead to changes in energy consumption. Besides, the interaction with external factors like gases from atmosphere may lead to some carbon dioxide absorption in case of lime-containing materials (concrete, hempcrete, …) [16,17].

The real durability of construction products can be significantly different from the theoretical and declared one [18]. ISO 15686-8 defines a methodology and factors to determine the service lifespan of construction products and building equipment. According to the literature review, many building-LCA studies refer to 50–100 years as a lifetime of buildings. The service life of 30 years is typically used for principal components of a building (e.g. floors, façades, and roof) [8] and products should be replaced or refurbished at their end of life using new technologies that have emerged.

Although the technical performances of building components may diminish during the building's long lifetime, this very longevity of the building implies that it will be able to benefit from technological innovations occurring after its original construction. The relevance of taking this prospective aspect into account in LCA for long time scale studies has been discussed by Frischknecht et al. [19]. Prospective factors should be considered for different scales and depending on the scope of the study. Replacement, refurbishment and also the treatment of construction waste products occurring several decades after the first construction may use new technologies that are more efficient in terms of energy consumption or environmental emissions. Thus, industrial and technological improvements should lead to long time scale scenarios with high environmental quality of the buildings.

Reducing energy consumption during the building component production and during its service lifetime is a continuing goal. Lowering the environmental load of the energy used is another improvement criterion. Heat production can use thermal resources like fossil fuels, biomass, and thermo-solar systems. A large panel of electricity production technologies exist, based on fossil or renewable resources. French electricity production depends strongly on nuclear power and is characterized by a low carbon footprint, with an annual average of 105 gCO_2 eq/kWh, compared to the power production technologies of other European countries, which are mostly based on fossil fuels. For example, the average carbon intensity of electricity consumed in Europe was 447 g CO_2-eq/kWh in 2013 [20].

To meet the target concerning the reduction of GHG emissions, the European Commission has proposed a framework for energy pathways towards 2050. Following this strategy, 75% of the European electricity consumption would be covered by renewable sources, with a shift in the electricity production mix and improvements in energy system efficiency [21]. Decarbonisation is also encouraged for heating and cooling systems to ensure that the goal of limiting climate change is achieved [22]. According to this study, increasing the share of district heating with respect to the total energy demand, and also accounting for the

Table 1
Dynamic elements of the "building system" from the state of the art.

	Authors	Time-varying parameters	Time horizon to account for time-varying parameters
Construction product and materials	[12–15,24]	Technical performances (thermal, acoustic, mechanical resistances of materials), Service lifetime of construction products and materials, Material quantities	Year to decade ~
HVAC (Heating, Ventilation, and Air-Conditioning) system	[25,26]	Energy efficiency of HVAC Generation and distribution system, Energy consumption, Service lifetime	Hour, day, month, season, to several decades
On-site electricity production (e.g. on-roof photovoltaic)	[27,28]	Electricity production by photovoltaic system	Hour, day, month, season to several decades
Occupant behaviour	[11]	Thermal management Typology of family Insulation material choices	Year to decade ~
Energy production (electricity and district heating and cooling)	[27,29,30]	Mix of energy production resources (Composition of each fuel type in a kWh of production)	Hour, day, month, season to several decades
Carbon sequestration in wood and biogenic carbon emission	[24]	Quantity of carbon dioxide absorbed by and emitted from wood	Several decades to century
Carbon sequestration in other materials	[16,17]	Quantity of carbon dioxide absorbed by e.g. lime-containing products	Years, several decades
Retrofitting scenario	[31]	Technical performances of materials	Decade ~
Demolition scenario	[24]	Energy recovery and recycling technologies	Decade ~

development of other heating systems (waste incineration, geothermal, solar thermal and industrial excess heat), would reduce carbon emissions at European level by 17–30% by 2050 with respect to the same heat demand level as in 2010. Also included in the scenario are other temporal changes in heat production systems: decreasing nuclear production, renewing power plants and existing combined fossil-fuelled heat and power (CHP) plants, and developing renewable heat production. In France, the national energy strategy aims to increase the proportion of renewable energy resources to 40% by about 2030 and reducing the nuclear production fraction from 75% to 50% by 2025 [23]. In terms of French district heating systems, the objective for 2030 is to cover 32% of district heat consumption by renewable energy resources. The quantity of renewable heat and cooling delivered in 2012 will be multiplied by five in 2030, which will represent 3.2 Mtoe (equal to 41.9 TWh).

Table 1 synthesises the state of the art studies in the field of buildings, which consider a temporal evolution of various factors susceptible to affect the environmental performances of a building system.

3. Considering temporal aspects in LCA applied to buildings

3.1. Time-related aspects in conventional LCA

LCA is the common method for evaluating products, services, and activities in terms of their potential environmental impacts throughout their life cycle, supported by ISO 14040–14044 standards [32,33]. According to the standards, LCA methodology is divided into four steps. i) Goal and scope definition. ii) Life cycle inventory compilation calculating material and energy balances at the level of the processes and of the environmental interventions (substances emitted into the environment and natural resources consumed), throughout the system's lifespan. While the LCI of background processes is generic and can be obtained from databases, the foreground process inventory is case-specific and must be obtained by data collection or specific modelling for the process/product under study. iii) Life cycle impact assessment based on methods for evaluating environmental impacts. iv) Interpretation of LCA results, as a consequence of time dimension included mainly in the first three steps of the methodology.

The analysis time span is the period used for each system studied, chosen in coherence with the lifetime of this system. It is specified in the first step of LCA, i.e. the definition of the goal and scope, and represents the period for which the established inventory is considered as reliable and the LCA results are considered valid (e.g. 50 years, the lifespan of a building). In the same manner, the time boundaries of a study situate the period of interest in time (e.g. a past or a future new system).

The conventional LCA approach considers stationary conditions, LCI being a list of environmental interventions without their occurrence time or spatial location. Environmental interventions, occurring in reality at different moments on the timescale and over different periods, are all considered equivalent with respect to the time span of analysis. In the context of rapid changes of the system properties, it is important to clearly indicate the temporality of data used, as they reflect specific conditions of the system under evaluation at a chosen moment. However, the practice of LCA is often limited by a lack of consistent and relevant data, especially for studies including prospective analysis.

Instead of being based on instantaneous and simultaneous inventory flows as in current LCA practice, the assessment can include a time dimension, integrated as temporally segmented inventories over the whole system life cycle. A time differentiated inventory, defined over distinct periods, takes account of the prospective evolution of systems over time. For the environmental evaluation of buildings having long lifetimes, time-dependent analysis with changes at different levels of systems e.g. technologies, economy, occupant behaviours, and political rules, can be implemented within conventional LCA by defining distinct scenarios over each time period of interest.

Various LCIA methods exist for calculating environmental impacts. The basic principle of all conventional methods is to provide a characterization factor (CF) for a given combination of substance/environmental compartment/effect (or impact). Then the substance amount (i.e. LCI) is multiplied by its CF to obtain the impact result. This is the basic principle of LCA. In such an approach, assumptions and simplifications were operated at the level of CF calculation, notably by considering the environmental mechanisms in steady state (static) conditions, or considering a fixed time horizon when an integral over time is required to calculate CF for some impact indicators (e.g. GWP – global warming potential). Conventional characterization factors are thus dependent on arbitrarily fixed time horizons (e.g. 20, 50, 100 years), which constitutes a strong limitation of the current LCIA methods. It is completely legitimate to raise questions like, "Does today's 1 kg of CO_2 emission have the same environmental impact as 1 kg emitted after 50 years?" Or, "Between 10 kg of CO_2 emission in a year and 1 kg of CO_2 emissions per year during 10 years, which case has the most impact at a precise date?" It is not possible to answer such questions within

conventional LCA and a new approach with fully dynamic modelling of environmental mechanisms is needed.

The relevance of taking account of the temporal dimension in the LCA, at both LCI and LCIA levels, has been discussed in recent studies [34–36]. In the following, we analyse how the temporal dimension is considered in previous studies dedicated to LCA of buildings.

3.2. Tools for LCA of buildings and their limitations

LCA is usually performed with dedicated software (e.g. SimaPro, Umberto, GaBi) and databases, ecoinvent being the most general and widely used in the European area. As mentioned in the introduction section, there are many LCA tools, software, and databases adapted to the construction sector; several tools that were available for this work and were included in the new methodology are presented here. ELODIE, a French LCA tool specific to buildings, is supported by INIES (http://www.base-inies.fr/iniesV4/dist/consultation.html), a public database of environmental and health data for construction products and building equipment. It includes Environmental and Health Product Declaration (EHPD: FDES in French) conformity and PEP ecopassport®. The data recorded in the FDES are values for environmental impact indicators declared in a voluntary way by the industrials, especially concerning newly constructed buildings. FDES do not contain inventory data. Data sets from INIES could provide more realistic and precise information for construction products than other generic LCI datasets such as ecoinvent. The future French energy and environmental regulations will be supported by the LCA method with its public inventory dataset for the construction sector. FDES data for construction products are used by ELODIE software for calculating environmental impacts of buildings.

Energy consumption during the service life can be calculated using models and software developed for thermal performances of buildings.

COMETH, a calculation engine for the simulation of a whole building's thermal performance, could be used to compute energy consumptions related to heating, cooling, domestic hot water, lighting and ventilation at an hourly time step. The tool is compliant with the French thermal regulations. This engine is easily configurable and allows to set the simulation boundary conditions, such as weather or occupant behaviour, and the building description, such as geometry, level of thermal resistance of its envelope and energy efficiency of equipment. The output of COMETH can be then used as an input in ELODIE - LCA software. Another French LCA tool for buildings, named EQUER, can be linked to a dynamic thermal simulation tool named COMFIE. This software allows time-varying energy production mixes and energy consumptions to be taken into account when assessing environmental impacts of building energy use at each time step, with historical weather data. As mentioned by Lasvaux [10] summarizing principal building-LCA software and its databases, many other examples of similar LCA calculation tools for buildings exist in different countries, e.g. One Click LCA (German), ATHENA (Canada), IMPACT (United Kingdom), which are based on different guidelines and contextual hypotheses (methodological choices, boundaries of an evaluated system, method of impact calculation, etc.). For example, LEGEP is a tool for LCA of buildings developed in Germany and it has an inventory dataset of more than 1000 construction materials complying with the European standard EN15804 [37] defining the method of environmental assessment of construction products.

None of these tools, however, considers any time-varying characteristics of construction products and equipment in the LCA study, nor can they differentiate the environmental interventions (emissions, resources) over time. Moreover, these existing tools do not allow for dynamic impact evaluations e.g. evolution of radiative forcing with time for climate change impact evaluation.

In addition to specifically dedicated tools for buildings, databases exist in the field of energy production at national and European level. The European Commission has initiated the project “New Energy Externalities Development for Sustainability (NEEDS)”, which gathers together international industrial life cycle inventories on future electricity supply systems. Several scenarios are proposed for the European energy mix by 2025 and 2050, which could be considered in a temporal perspective in order to assess the influence of the grid mix evolution on LCA results.

3.3. Different ways of considering time in LCA of buildings

Scheuer et al. [38] mentioned that future LCA studies should attach more and more importance to accounting for i) change in demand for materials and energy, ii) technical performances of energy services and equipment, and iii) material burdens due to changes in the foreground system e.g. choices of material, service lifetime of building components, as well as in the background system, e.g. production efficiencies of building materials. While authors have argued their proposals to integrate these dynamics in LCA, they did not have access to operational calculation tools to implement them in an appropriate LCA framework.

Frijia et al. [26] investigated the contribution of manufacturing and construction phases to the life cycle energy use. They proposed different functional units for a residential building, including all domestic functionalities or only heating and cooling systems, to calculate the operational energy use. They also assumed, in their case study, annual improvements in the energy efficiency of heat pumps and air conditioning systems towards 2052, based on public data from the U.S. Department of Energy and periodic replacement of HVAC (Heating, Ventilation, and Air-Conditioning) systems by advanced technologies. Their LCA case study of residential houses revealed that, using an adapted functional unit, which only included heating and cooling systems with a consideration of technological improvement, the share of embodied energy use could be far higher than in previous studies, which were based on the conventional functional unit.

Collinge et al. [29] proposed a dynamic LCA framework integrating temporal variability of industrial processes for energy production and the influence of time on climate change impact calculations. The development of their dynamic LCA method was based on the conventional matrix-based calculation of LCA [39] and consisted of calculating the inventory and impacts by time periods, i.e. a scenario approach. The functional units and reference flows were considered as parameters that could vary with time from one period to another. They exploited existing public data on dynamic energy productions (time variations of the grid electricity mix), and consumptions and related environmental interventions to obtain a distinct LCI per time period. Temporal variations of processes in the background system (energy production industry) were considered, as were different shares of energy resources over time (the supply chains). The building use phase was studied with particular attention due to the important environmental impact generated by energy consumption in this phase. Time-adjusted global warming potentials were used to calculate climate change impact following Kendall's method of time horizon correction [40], and using seasonal characterization factors for photochemical ozone formation [41]. This work brought out the importance of considering time in LCA of buildings. However, access to the specific building data (e.g. energy consumption, emissions) and the separate collection of inventory data for many periods might be the main limitation of their work.

Fouquet et al. [24] performed a comparative study of the static versus dynamic LCA for three low-energy buildings: 1) concrete cavity wall, 2) concrete double wall and 3) timber frame. This study also addressed the relevance of accounting for a temporal profile of CO_2 balance through the uptake due to the growth of trees until the release into the atmosphere at their end of life. The scope of the CO_2 balance should be well defined by considering forest management (i.e. timing of CO_2 uptake) and waste management scenarios at the building end-of-life (i.e. landfilling or incineration of woods leading to emissions of biogenic carbon dioxide), which would lead to significant differences in the results calculated for climate change impact. Scenarios of grid mix

Table 2
Identification of key dynamic characteristics of a building system to be integrated into an LCA study.

1. Occupant behaviour scenario	2. Construction products	3. Energy equipment	4. Energy mix scenario	5. Carbon uptake/ emission	6. End of life technologies
• Typology of family • Presence time of occupants • Thermal comfort level	• Degradation of technical performances of building components • Replacement and refurbishment with new technology	• Integration of renewable energy systems • Deterioration of production capacity of energy equipment	• Modifications of energy mix (electricity and heat) in the long term, based on national strategies	• Carbon uptake during the growth of trees • Carbon uptake by construction products • Biogenic carbon emission at the end of life	• Improved recycling rate or energy recovery can be integrated

were considered at time horizons of 2025 and 2050 based on given prospective LCI data sets from the ecoinvent database and from the publicly available database, NEEDS. They also paid particular attention to possible technological innovation in the background system related to cement production using an improved production technology. Time-dependent CFs were used for climate change impact calculations, following the method proposed by Levasseur et al. [42]. With this specific case study, it was acknowledged that dynamic LCA could alter the conventional interpretation of LCA results, thus providing a better understanding of the environmental behaviour of building systems.

Electricity consumption and the method used for its production exhibits marked temporal variation in both the short term, e.g. due to daily occupant behaviour or weather conditions, and the long term, e.g. due to the increase in renewable energy technology in electricity mix production, and due to climate change. Integrating renewable energy and auto-consumption systems in buildings, e.g. photovoltaic system on the roof, requires more detailed analysis of LCI data over time [27]. The high temporality of this energy aspect has always been considered in LCA studies. Peuportier and Herfray [43] developed a dynamic and prospective LCA model to exploit historical data on public electricity (provided by Electricity Transmission Network) differentiated in given time steps from an hour to a year. Energy consumptions of testbed buildings were obtained at hourly or monthly time steps and then injected into the LCA study based on EQUER software in order to evaluate global warming potential (GWP). The impact was calculated by multiplying environmental emissions at each time step (from the French electricity grid) by the corresponding characterization factor (for instance, CF = 1kgCO_2-eq/kg$CO_2$for carbon dioxide). The dynamic electricity production mix model was based upon time-varying productions for each fuel type and based on a given atmospheric temperature. Following this study, Roux et al. [28] improved the approach by integrating a temporal variation of local energy production by the on-roof photovoltaic system. The improved methodology was applied to testbed cases of three low-energy buildings to evaluate their environmental performances and acknowledged the discrepancy between static and dynamic LCA results. The time step of the LCI model concerning the energy consumption and production was considered as a key element for the relevance of dynamic LCA results and should be adapted to each case study with respect to local conditions (e.g. climate, energy equipment, occupant behaviour). However, this study was limited to only one year for the energy use phase of buildings. Nevertheless, these studies have the virtue to include commonly used simulation tools in the field of energy efficiency of buildings in a temporal representation of the life cycle inventory, moving forward with respect to other studies [44,45] in which the simulation results of dynamic energy demand are used in LCA in an integrated form, as a single total energy value over the building's lifecycle.

Recently, Su et al. [46] assessed the state of the art of dynamic LCA for buildings, mentioning that the recent developments lack a temporal consideration of socio-economic parameters (technological progress of building components, occupant behaviour). They also proposed the use of time-varying weighting factors in the LCIA phase. These factors could be used to attribute different weights to different impact categories in order to transform them into a single indicator e.g. monetizing LCA results in order to compare systems based on a single end-point impact. However, the authors did not identify the appropriate tools, i.e. models, software, databases or data providers, they expected to use when implementing the proposed approach. Their development still remains only a theoretical concept without a concrete application to a case study.

4. Discussion and presentation of new approach

4.1. General trends from the state of the art

While the LCA method is a powerful tool for environmental performance evaluation, the current practice of LCA has not integrated a proper analysis of the environmental performance of systems with a longer time scale, such as building systems. Several of the previous building-LCA studies considered temporal characteristics but limited them rather to the LCI or LCIA steps. Another common limitation of these previous studies is that several temporal aspects are considered only in the foreground system or targeted on a few background processes (e.g. future technological improvement of a particular process). The general temporal behaviour of the supply chains with their time-shifted occurrence is not considered although, on a long lifetime scale, emissions occurring at different time horizons would have very different impacts. Concerning the LCIA step, only a few environmental flows of existing inventory data related to the case studies have been used, most of them only for climate change impact. The existing proposed methodologies lack a general operational method and calculation tools, i.e. software, coherent temporal databases, that could be applicable to any case study.

4.2. Identification of key dynamic aspects

Following the state of the art, Table 2 synthesises the key temporal aspects that might influence the environmental performance of a building life cycle. Descriptions of the elements are given one by one below.

4.2.1. Type of occupancy

Energy consumption occurring over the whole lifetime of buildings is determined by the typology of occupancy (e.g. number of inhabitants, age) and the occupant behaviour, among other things. The current practice in building-LCA accounts for dynamic behaviours of occupants only within a year and occupant behaviours are assumed to be cyclic over the lifetime a building. It is thus relevant to integrate scenarios of occupancy over a long time scale, i.e. evolution of the occupant typology and evolution of the occupant behaviour, into the dynamic assessment.

4.2.2. Building components

Energy consumption levels should be also analysed with regard to degradations of technical performance of building components e.g. degradation of thermal resistance of insulation materials over time. Then, considering the future improvement of building technologies and materials, periodical replacement and refurbishment of the building is envisioned with new technologies to satisfy thermal comfort levels and building functions. Although replacement/refurbishment is already included, few previous LCA applications account for technological and technical evolution in time. Insulation materials with higher thermal performances would reduce energy consumption levels, but might need more or less energy and materials in the background system for their fabrication, leading to unexpected changes of the environmental impacts with respect to current practice. For these reasons, it is relevant to integrate potential improvements of technologies and materials into the dynamic LCA at the building component level.

4.2.3. Energy production equipment

The European and French energy and environmental regulations envision an ever increasing percentage of renewable based energy production, and also the integration of more local renewable energy systems, as discussed in section 2. The degradation of the production capacity of existing energy production equipment over time would negatively affect the environmental impacts over the whole life cycle of a building. On the other hand, progress at the level of energy production technologies and equipment could reduce the environmental impacts of such systems and consequently of the buildings. After reviewing some previous studies, we propose the integration of technological changes in energy production equipment into the dynamic assessment.

4.2.4. Energy mix

Scenarios of the electricity and district heat production mix on a long time scale should be considered. Renewable energy resources would make up more and more of the grid mix to meet the objective of reducing GHG emissions by energy production systems. Modelling different energy mix scenarios and considering them in building LCA would give a range of variation of results and help to make environmental assessment results more robust.

4.2.5. Biogenic carbon emission and carbon uptake

The current LCIA methods (e.g. EN15978) do not include biogenic carbon (e.g. carbon dioxide emissions from biomass in the GWP calculation) as a factor of climate change. However, as mentioned by Ref. [24], for a building composed of significant amounts of wood, it is relevant to take all flows of CO_2 from the tree growth phase (CO_2 uptake from atmosphere) to the end of the life of the building (CO_2 emissions into the atmosphere). Carbon that is sequestrated in wood during tree growth would be released into the air through the combustion or degradation of wood-based materials at the end of life stage. Carbon dioxide can also be absorbed from the atmosphere by materials having a high content on basic substances, e.g. rich on lime. This process is slow and takes place over decades. For these reasons, it is important for a time span large enough for LCI to be included in the scope of the study in order to encompass all these processes, from forestry management to end of life scenarios. A dynamic LCI approach will allow these different processes to be placed on a time scale. Notably CO_2 uptake and emissions will be separated by long periods of time (e.g. more than 100 years in case of wooden buildings) and no compensation will operate between them (in conventional LCA, CO_2 emissions and uptake take place at the same time and, being of opposite sign, they compensate each other when summed up in the inventory step). This will have a significant influence on the results for climate change impact, in contrast with conventional LCA.

4.2.6. End of life technologies

There are many kinds of technologies for waste treatment at the end of the life of building components and the building itself, depending on the nature of waste (e.g. inert waste, dangerous and non-dangerous waste) and the type of materials present in the waste (e.g. concrete, wool, plastic, etc.) [47]. After long lifetimes of several decades to 100 years, end of life technologies and related infrastructures (e.g. recycling processes, energy production mix) will probably have evolved with respect to current technologies. The current practice of LCA can take into account prospective improvements of technologies into the calculation of inventory data. However, ignoring time lags of emissions between the construction and the end-of-life phases, as performed in conventional LCA, would bias impact calculations, especially for climate change impact, by compensations (as explained above for the case of biomass) or by the instantaneous and simultaneous emission hypothesis.

4.3. Principles of the dynamic LCA method

A dynamic LCA method was recently proposed, providing adapted calculation tools. Tiruta-Barna et al. [48] proposed a temporal model for LCI, which considers the complex supply chains and processes that compose the life cycle system, for both foreground and background processes. This calculation tool, named DyPLCA (available at http://dyplca.pigne.org/), delivers the dynamic inventory, i.e. environmental interventions by substance/process and aggregated by substance, distributed in time. The dynamic LCI model can be linked to a conventional LCA database (ecoinvent for instance), which facilitates its use by LCA practitioners. A temporal database is included in DyPLCA, containing the time-dependent parameters of processes and supply chains associated with the datasets existing in ecoinvent 3.2.

At present, the DyPLCA tool can be used in the following ways. 1) The life cycle system can be completely modelled by the user on the DyPLCA web interface with any desired data. 2) An automatic mode allows ecoinvent data sets to be used (including different allocation models). In this case, the life cycle system is first modelled with SimaPro LCA software, then the technological matrix and the environmental intervention matrix can be extracted and uploaded within the DyPLCA tool (embedding the complementary temporal database).

Whatever the mode of use, the results provided by DyPLCA as environmental interventions distributed in time are then used with adapted LCIA dynamic models. Currently, there are very few dynamic models for calculating impact indicators in function of time. In Refs. [49–51] a dynamic climate change model and a dynamic toxicity model are developed and applied with the dynamic LCI to several case studies. In these methods, data and phenomenological dynamic models were implemented: (i) from IPCC [52] for climate change, and (ii) from the USEtox® 2 model [53,54] for toxicity impact categories. The complete framework was successfully tested on case studies by Ref. [55] and, from now on, it can also be used for building systems. These dynamic LCIA methods were implemented with the DyPLCA tool.

The proposed methodology for dynamic LCA of buildings relies on the dynamic LCA approach and tools presented above.

4.4. Proposed methodology for dynamic LCA of buildings

In the building sector, temporal characteristics of systems can be summarized at three levels: building technology level (e.g. technical performance degradations and technological innovations), end-user level (e.g. occupant behaviour) and external system level (e.g. infrastructures, energy mix). These characteristics are represented by temporal parameters of buildings explained in the previous section and in Table 2, and should be integrated into fore- and background parts of the inventory. Many of the time variable parameters considered in the present framework are related to technologies and materials of building components, which contribute significantly to the total impact of a

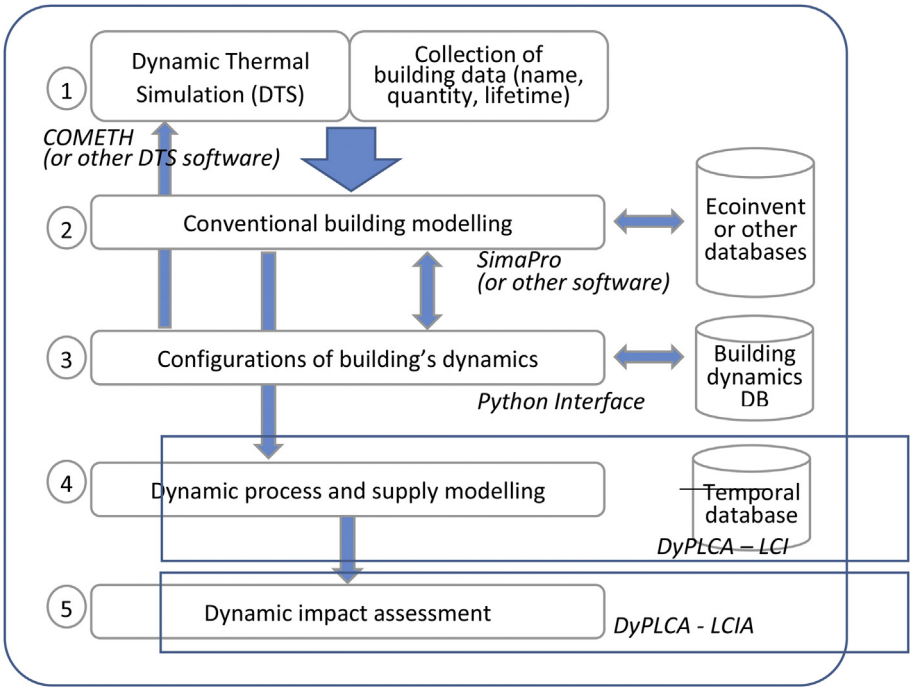

Fig. 1. Main steps of the proposed methodology for Dynamic LCA of buildings.

building system. On the other hand, dynamic energy consumption and energy mix evolution with technological breakthroughs related to renewable resources and energy management systems (energy storage, smart grids, etc.) are also important contributors. This is because the impact from energy use during the building operational phase depends greatly on the energy production technologies (the background system in LCA). The proposed general framework for the dynamic LCA of buildings is shown in Fig. 1.

Step 1 (Data calculation and collection): Annual energy consumption at the level of a building can be calculated with different time steps, e.g. hourly or daily, thanks to a dynamic thermal simulation tool. COMETH will be used in this methodology as it allows to easily take into account long-term temporal changes in the design of the building's thermal model (boundary conditions based on French data and physical properties of the building). In parallel, data of the reference flow of a studied functional unit should be collected, including product and equipment names, quantity and service lifetime. For example, 20 cm of mineral-based insulation materials for 160 m^2, whose service lifetime is 30 years, satisfying a thermal resistance level for a whole building with respect to the French national thermal regulation.

Step 2 (Static model of the life cycle system): The building life cycle system could be modelled in SimaPro LCA software or other LCA tools following the conventional matrix-based LCI calculation, with energy and material balances calculated and collected in the first step. The different life cycle stages are clearly identified with the different associated activities. For example, the usage of window's glazing should appear in the phase of construction and also in replacement or renovation phases. Thus, this process appears repeatedly in the life cycle system, but at different moments in time, which will be determined in step 4. For specific modelling in the sector of buildings, data sets from other sources can be used, e.g. FDES. However, despite the advantage of more building-specific content, the use of FDES is currently hampered by the form of the information contained, i.e. the lack of elementary flows. Concerning the foreground part of the life cycle system, any data set (collected on site, modelled, from specific databases) can be used, as is currently done in static conventional LCI modelling.

Step 3 (Dynamic model of building system): This step introduces the temporal dimension in the system modelled in step 2. The key dynamic parameters described in Table 2 are considered. Technological change of construction products and energy equipment will mostly be considered. For example, a renovation of the wall would use new insulation materials. Therefore, this evolution of thermal resistance of a building's envelope would first affect the energy consumption level. Secondly, material balances of advanced technologies used in renovation should be different from those used in the construction phase. This means that the technological and environmental matrix of the inventory both for fore- and background systems should be recalculated to account for time-dependent scenarios. With this in mind, a database of the temporal behaviour of buildings, "building dynamics DB" in Fig. 1, will be developed together with an interface. This database will contain dynamic and prospective parameters of building components (e.g. degradation rate of thermal resistance of insulation materials over 25 years), energy mix (e.g. future proportions of electricity generation resources), occupant behaviour (e.g. potential future change of occupancy profiles), or regulations (e.g. management of specific materials) that can potentially modify the datasets of technology and environment matrixes in conventional LCI databases. Moreover, the database will contain ranges of variation of those parameters, allowing to further investigate the uncertainty on the results. With respect to actual data sets of LCI, such as ecoinvent, that are founded on static or averaged inventory values, the objective of the building dynamics DB will be to account for dynamic and prospective aspects of a building system in a consistent way for all building-LCA studies. An interface making a connexion between a building's LCI previously modelled in Step 2 and the building dynamics DB would greatly help to update LCI with scenarios of a building system over time.

Step 4 (Dynamic model of the supply-chain): Technological and environmental matrix, created from the model in SimaPro or other LCI calculation tool, is then used as input to the DyPLCA tool. DyPLCA contains a database of temporal parameters associated with processes in ecoinvent 3.2, useful for the LCI temporalization of the background processes and supply chains. The building, with its three stages, i.e. construction, use and end of life, represents the foreground part of the life cycle system. The temporal characteristics of the foreground (processes and supply chains) are defined by the user; for example: construction takes 11–13 months [56] before the building operation phase

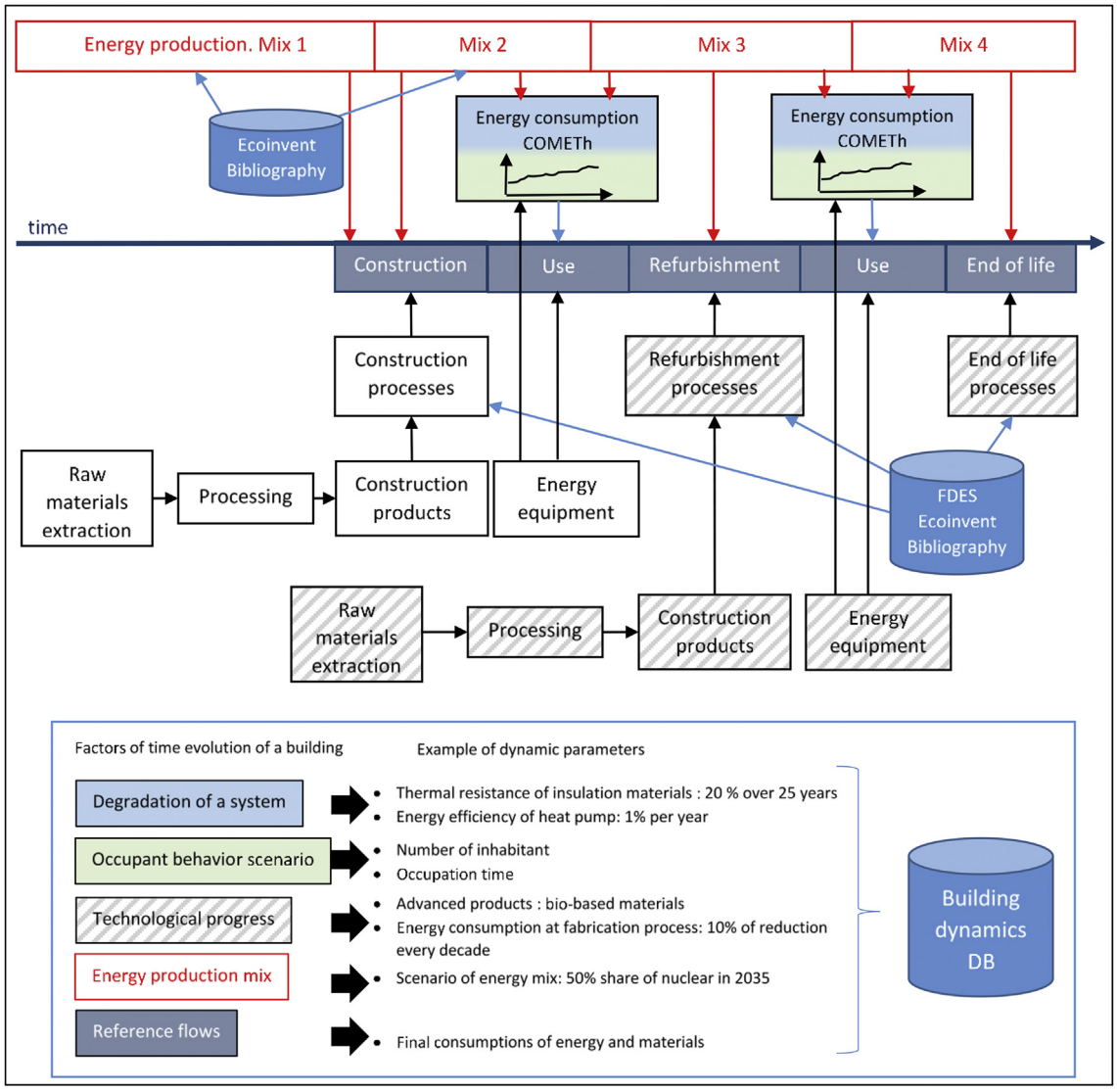

Fig. 2. Time dimension of a building system and methodology application.

starts, considering that there is no time lag between the end of construction and the beginning of the building operation phase; renovation of floors occurs after 50 years and takes several months, etc. The output from DyPLCA is environmental intervention flows (e.g. kg/day) according to time (in csv format).

Step 5 (Dynamic model of the impact assessment): Using the temporal discrete LCI (output from DyPLCA), temporal indicators for environmental impacts will be calculated. As mentioned before, dynamic climate change, human toxicity, and ecotoxicity are the impact categories for which dynamic models have been implemented. In addition, the inventory can be also used for classical impact assessment by calculating the partial or total integral of the flows over time.

Fig. 2 presents in a very simplified manner the life cycle of a building placed on the time scale, with its different stages: construction, use, refurbishment, and end of life phases. Various processes are involved in these foreground stages, each of them with raw material extraction and processing steps in the background part of the life cycle system. Energy production is included in the background as well. The present time (or time zero) can be placed anywhere on the timescale following the user's convenience: the study can be completely prospective (building in the future), retrospective (building in the past), or building at its different stages in the present time. Dynamic LCA can thus differentiate between past, present and future environmental impacts generated. Each process entering the life cycle at a given point in time can be specific for that time (obviously, if data exists).

The different tools specific for the building are also placed on the scheme. Inventory data for building related processes comes from databases like FDES, ecoinvent or others, and from literature. Inventory data for very background processes (e.g. electricity production) are rather generic and comes from ecoinvent database. These static data are transformed in time-dependent data thanks to the building dynamics DB and then of the DyPLCA tool. Technological and elementary flows of foreground processes are calculated at the process level with the consideration of dynamic parameters, leading to variable reference flow per process (e.g. decrease of the heat demand in use phase due to climate change, occupancy, etc.). The factors and parameters affecting the time evolution of building (i.e. the reference flows of different processes in the building's life cycle) are collected in the building dynamics DB. These parameters are used with appropriate models for calculation of material and energy consumption at different points in time (i.e. recalculate the technological, elementary and reference flows of processes). For example, processes concerned by degradation of their performances are marked in blue and processes concerned by occupant behaviour in green – both factors being included in building dynamics DB.

As earlier mentioned, energy consumptions of the building are

calculated thanks to a dynamic thermal simulation tool - here COMETH software is an example - by taking into account temporal degradation of thermal insulation and energy efficiency of HVAC system. Considering for example that zero point in time corresponds to the beginning of the construction, processes marked on grey in Fig. 2 are ones for which technological progress can be considered as prospective scenarios. Technological progress can be envisaged not only for building products but also for the HVAC system equipment. The changes in the HVAC system (if known) can be integrated into the simulation of end-use energy consumptions. Also, technological progress can occur in product manufacturing processes, leading to reductions in energy and material consumptions in the background processes. The energy mix scenarios in the long-term are applied to both end-use energy consumption and energy consumption at the background processes of a building.

After the calculation of specific material and energy flows, the system is modelled as for a conventional LCA using e.g. the SimaPro software. This modelling includes many subsystems corresponding to periods with a predefined duration, e.g. 1 year, or 10 years (user defined values), each period being characterized by constant parameters for all processes involved in the period. In other words, the time scale is gridded in order to define periods of constant characteristics. After that, technology (technological flows) and environmental (environmental intervention flows) matrixes are generated by the conventional LCA software and imported into DyPLCA tool. DyPLCA tool adds temporal parameters for the supply chain and environmental interventions, and performs dynamic LCI calculation. The result, in form of environmental interventions distributed in time, is the used for dynamic impact calculation with a Python home-made software.

The proposed methodology takes the temporality of processes and value chains composing the life cycle system into account. The expected results, in terms of inventory temporalization and time-dependent environmental impacts, will allow a better understanding of the building system and a more realistic evaluation of environmental performances. However, one of the limitations is that the state of research in the field of methodological development of dynamic LCA does not allow the calculation of all impact categories commonly assessed by conventional LCA, since dynamic models actually exist only for climate change and toxicity categories. A shift in the common LCA practices is needed in order to foster the development of such advanced tools. French FDES, being collected directly from manufacturers, provide reliable LCIA data sets for construction products and equipment but LCI data (technological and environmental flows) is hardly publicly accessible today. Another difficulty in performing an environmental assessment with the proposed framework concerns the data collection of building system dynamics since the dynamic approach is new and, obviously, data are lacking.

During the long lifetime of buildings, technologies in the field of energy production, waste management or construction products could be improved or innovative technologies could replace the current ones. The limited knowledge on the future implemented technologies induces uncertainties on LCA results whatever the approach, conventional or dynamic. In this regard, the dynamic approach can evaluate the time limit from which the uncertainty rises due to technological changes.

Another source of uncertainty on LCA (conventional and dynamic) results is the quality of inventory data obtained from databases, modelling, on-site collection, etc. Besides these quantitative aspects, common for both LCA approaches, the dynamic LCI calculation presents uncertainties related to the time dimension, i.e. specific dynamic behaviour of processes, duration and delays in the supply chain. The new database for building dynamics DB (in Fig. 1) will contain such time-dependent parameters and their ranges of variation. Sensitivity analysis allows the identification of key parameters of the systems and allowing simulation of plausible scenarios as well as uncertainty estimation.

Finally, the added value of a dynamic approach lies on the complementary information it brings out which is the temporal distribution of environmental interventions and impacts, enriching as such the conventional LCA approach. More, the integration of time dimension on the impacts' modelling provides a much more realistic result as the "potential" impact in conventional LCA.

Still being under development, the full capabilities of the dynamic approach are not completely known and exploited by now, numerous case applications on different fields of activity being necessary to this end. In the field of buildings, it could help to define mitigation strategies, as for example: i) possibility to intervene in the future on a given system to avoid/diminish emissions/impacts; ii) possibility to schedule processes in order that their temporality diminishes the impacts – for example on climate change the intensity of the impact depends on the emission profile (high pic or flat step); iii) choosing between materials - biogenic carbon versus fossil one, management of biogenic carbon in time in order to favour its capture previous to its utilization, etc. Scheduling the carbon emission and capture is a very important dynamic aspect which greatly influences the climate change impact result.

5. Conclusions

This study first focused on the temporal characteristics of building systems. Our points of view regarding the time dimension of building systems can be summed up in three levels.

The first is *the temporal evolution at the level of the building* itself. Technical performances related to construction products and energy equipment degrade over the long lifetime of buildings. The occupants of a building are thus required to carry out regular maintenance, replacement, and refurbishment of the building system to satisfy a building function. While the degradation of technical performances of buildings needs to be pointed out, it should not be forgotten that technological improvements of construction products and end-user energy systems should also occur because buildings have a lifetime long enough to take advantage of new technologies.

The second concerns *temporal parameters of the building's end-users*. Changes of occupants and their behaviour (family size, the schedule of their occupation of the building, thermal system management i.e. thermal comfort level and time of occupants' presence in the house) engender changes in energy consumption and use of building materials.

Third, these previous two types of time dimension should be considered with respect to *change of the background system of the building*. The temporal evolution of the energy production mix, climatic conditions or energy, and environmental regulations are factors influencing not only building technical performances but also occupant behaviours.

In conclusion of the literature review, a building system is a long life system which evolves in time and for which environmental performance is difficult to assess given the limitations of the commonly used environmental assessment tools. The LCA method has been extensively used for evaluating the environmental impacts of buildings but the lack of a temporal dimension constitutes a considerable limitation. Very few studies have addressed this question so far. Most temporal LCA studies have considered prospective scenarios of technological improvements in fore- and background systems (e.g. energy efficiency of a heating system and cement production) and occupant behaviour (e.g. heating system management) in the long term. Only case studies based in France and the United States have been presented. One study integrated short-term variation of the energy mix composition in LCA, while another showed that it is important to take biogenic CO_2 balance into account over the life cycle of wood-based buildings. The few studies performed so far concerning the building system and its temporal behaviour have proposed an improvement of LCA, which can go beyond the current state of LCA research. However, they do not propose any operational, reproducible tools for performing effective temporal evaluations.

In the present work, we propose a new framework for dynamic LCA applied to building systems. This new methodology represents the most complete temporal approach for environmental assessment in the building domain. The framework integrates the time dimension at the

level of different steps of LCA.

The life cycle inventory combines an existing environmental dataset for the background processes (ecoinvent v3.2) and LCA software with a new database enabling temporal behaviours of the building system to be parameterized considering technology, occupants, energy mix, and regulations. The DyPLCA tool enables temporal characterizations of processes and supply chains at the background level and for the foreground processes with user-defined temporal parameters. The calculated temporalized LCI is then used in LCIA step to calculate time-dependent environmental impact indicators, i.e. for climate change and toxicity categories. To integrate more specificities of the construction sector, using existing tools and a database specific to the LCA for buildings, e.g. ELODIE (software using FDES as input data) and INIES in France, would help to make dynamic LCI modelling of buildings more case-specific. However, the implementation of dynamic LCA with these specific tools is still limited due to lack of basic information like the elementary flows or too high a degree of data aggregation. Therefore, the next methodological improvement challenges of dynamic LCA for buildings are the exploitation of FDES data to be used in a dynamic LCI calculation, e.g. inclusion of detailed information on inventory data, and the development of a tool to calculate a dynamic LCI based on FDES.

The present methodology could be applied to building case studies and, besides providing the impact results, would enable the concomitant development and enriching of the database of dynamic parameters of the building system. However, there is also a need to investigate the sensitivity of LCA results with respect to dynamic parameters for a deeper understanding of dynamic impact behaviours. Identifying the most influential dynamic parameters of building systems could be useful for model simplification and as a guide for applications of dynamic LCA for buildings. Finally, improvements will be brought up by case studies, and the existing tools will be adapted and upgraded for building systems.

Acknowledgment

We gratefully acknowledge the funding of this work by the French National Research Agency (ANR-13-IS09-0007-01/DyPLCA).

References

[1] B. Peuportier, Life cycle assessment applied to the comparative evaluation of single family houses in the French context, Energy Build. 33 (2001) 443–450, https://doi.org/10.1016/S0378-7788(00)00101-8.
[2] G.P. Gerilla, K. Teknomo, K. Hokao, An environmental assessment of wood and steel reinforced concrete housing construction, Build. Environ. 42 (2007) 2778–2784, https://doi.org/10.1016/j.buildenv.2006.07.021.
[3] G.A. Blengini, Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy, Build. Environ. 44 (2009) 319–330, https://doi.org/10.1016/j.buildenv.2008.03.007.
[4] R.J. Cole, P.C. Kernan, Life-cycle energy use in office buildings, Build. Environ. 31 (1996) 307–317, https://doi.org/10.1016/0360-1323(96)00017-0.
[5] K. Adalberth, Energy use during the life cycle of single-unit dwellings: examples, Build, Environ. Times 32 (1997) 321–329, https://doi.org/10.1016/S0360-1323(96)00069-8.
[6] French Ministry of the Environment, Minisètre de la Transition Ecologique et Solidaire, (2016) http://www.batiment-energiecarbone.fr/.
[7] JRC European Commission, Level(s): a Common EU Framework of Core Sustainability Indicators for Office and Residential Buildings : Parts 1 and 2, Introduction to Level(s) and How it Works (Beta v1.0), (2017) https://publications.europa.eu/en/publication-detail/-/publication/f3c2fc97-f102-11e7-9749-01aa75ed71a1/language-en/format-PDF , Accessed date: 12 January 2018.
[8] JRC European Commission, Level(s): a Common EU Framework of Core Sustainability Indicators for Office and Residential Buildings : Part 3, How to Make Performance Assessments Using Level(s) (Beta v1.0), (2018) https://publications.europa.eu/en/publication-detail/-/publication/3bff9f38-f1cc-11e7-9749-01aa75ed71a1/language-en/format-PDF , Accessed date: 12 January 2018.
[9] CEN, EN 15978:2011, Eur. Comm. Stand, (2011).
[10] S. Lasvaux, Étude d'un modèle simplifié pour l'analyse de cycle de vie des bâtiments, (2012).
[11] T. de Meester, A.-F. Marique, A. De Herde, S. Reiter, Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate in the northern part of Europe, Energy Build. 57 (2013) 313–323, https://doi.org/10.1016/j.enbuild.2012.11.005.
[12] J. Toman, A. Vimmrová, R. Černý, Long-term on-site assessment of hygrothermal performance of interior thermal insulation system without water vapour barrier, Energy Build. 41 (2009) 51–55, https://doi.org/10.1016/j.enbuild.2008.07.007.
[13] F. Stazi, F. Tittarelli, G. Politi, C. Di Perna, P. Munafò, Assessment of the actual hygrothermal performance of glass mineral wool insulation applied 25 years ago in masonry cavity walls, Energy Build. 68 (2014) 292–304, https://doi.org/10.1016/j.enbuild.2013.09.032.
[14] H.-J. Choi, J.-S. Kang, J.-H. Huh, A study on variation of thermal characteristics of insulation materials for buildings according to actual long-term annual aging variation, Int. J. Thermophys. 39 (2018), https://doi.org/10.1007/s10765-017-2318-3.
[15] Sandrine Marceau, Sabine Caré, Pilar Lesage, Matériaux Biosourcés et Naturels Pour Une Construction Durable, (2016).
[16] K. Pommer, C. Pade, Guidelines - Uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete vol. 5, (2005) https://www.dti.dk/reports-on-co2-uptake-from-the-carbonation-of-concrete/guidelines/18487 , Accessed date: 10 August 2018.
[17] F. Collins, Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint, Int. J. Life Cycle Assess. 15 (2010) 549–556, https://doi.org/10.1007/s11367-010-0191-4.
[18] A. Talon, Evaluation des scénarii de dégraation des produits de construction, (2006).
[19] R. Frischknecht, S. Büsser, W. Krewitt, Environmental assessment of future technologies: how to trim LCA to fit this goal? Int. J. Life Cycle Assess. 14 (2009) 584–588, https://doi.org/10.1007/s11367-009-0120-6.
[20] A. Moro, L. Lonza, Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles, Transport. Res. Part Transp. Environ. (2017), https://doi.org/10.1016/j.trd.2017.07.012.
[21] European Commission, Energy Roadmap 2050, (2012).
[22] H. Lund, D. Connolly, B. Vad Mathiesen, P. Alberg Østergaard, B. Möller, S. Nielsen, U. Persson, D. Nilsson, S. Werner, D. Trier, Heat Roadmap Europe 2050, (2012).
[23] France National Low-carbon Strategy, (2015).
[24] M. Fouquet, A. Levasseur, M. Margni, A. Lebert, S. Lasvaux, B. Souyri, C. Buhé, M. Woloszyn, Methodological challenges and developments in LCA of low energy buildings: application to biogenic carbon and global warming assessment, Build. Environ. 90 (2015) 51–59, https://doi.org/10.1016/j.buildenv.2015.03.022.
[25] D. Beloin-Saint-Pierre, A. Levasseur, M. Margni, I. Blanc, Implementing a dynamic life cycle assessment methodology with a case study on domestic hot water production, J. Ind. Ecol. (2016), https://doi.org/10.1111/jiec.12499.
[26] S. Frijia, S. Guhathakurta, E. Williams, Functional unit, technological dynamics, and scaling properties for the life cycle energy of residences, Environ. Sci. Technol. 46 (2012) 1782–1788, https://doi.org/10.1021/es202202q.
[27] Marine Fouquet, Réflexions et contributions méthodologiques à l'ACV de batiments neufs : modélisatino du contributeur énergie, (2015).
[28] C. Roux, P. Schalbart, B. Peuportier, Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house, J. Clean. Prod. 113 (2016) 532–540, https://doi.org/10.1016/j.jclepro.2015.11.052.
[29] W.O. Collinge, A.E. Landis, A.K. Jones, L.A. Schaefer, M.M. Bilec, Dynamic life cycle assessment: framework and application to an institutional building, Int. J. Life Cycle Assess. 18 (2013) 538–552, https://doi.org/10.1007/s11367-012-0528-2.
[30] C. Roux, P. Schalbart, E. Assoumou, B. Peuportier, Integrating climate change and energy mix scenarios in LCA of buildings and districts, Appl. Energy 184 (2016) 619–629, https://doi.org/10.1016/j.apenergy.2016.10.043.
[31] F. Stazi, C. Di Perna, P. Munafò, Durability of 20-year-old external insulation and assessment of various types of retrofitting to meet new energy regulations, Energy Build. 41 (2009) 721–731, https://doi.org/10.1016/j.enbuild.2009.02.008.
[32] ISO 14040:2006, ISO 14040:2006, Environ. Manag. - Life Cycle Assess. - Princ. Framew. Int. Stand, (2006).
[33] ISO 14044:2006, ISO 14044:2006, Environ. Manag. - Life Cycle Assess. - Princ. Framew. Int. Stand, (2006).
[34] D. Beloin-Saint-Pierre, A. Levasseur, A. Pinsonnault, M. Margni, I. Blanc, How can temporal considerations open new opportunities for LCA industry applications? 6th Int. Conférence Life Cycle Manag., Gothenburg, Sweden, 2013, p. 4 https://hal-mines-paristech.archives-ouvertes.fr/hal-00920310.
[35] P. Collet, L. Lardon, J.-P. Steyer, A. Hélias, How to take time into account in the inventory step: a selective introduction based on sensitivity analysis, Int. J. Life Cycle Assess. 19 (2014) 320–330, https://doi.org/10.1007/s11367-013-0636-7.
[36] A. Pinsonnault, P. Lesage, A. Levasseur, R. Samson, Temporal differentiation of background systems in LCA: relevance of adding temporal information in LCI databases, Int. J. Life Cycle Assess. 19 (2014) 1843–1853, https://doi.org/10.1007/s11367-014-0783-5.
[37] CEN, EN 15804:2012, Eur. Comm. Stand, (2012).
[38] C. Scheuer, G.A. Keoleian, P. Reppe, Life cycle energy and environmental performance of a new university building: modeling challenges and design implications, Energy Build. 35 (2003) 1049–1064, https://doi.org/10.1016/S0378-7788(03)00066-5.
[39] R. Heijungs, S. Suh, The Computational Structure of Life Cycle Assessment, Springer Netherlands, Dordrecht, 2002, https://doi.org/10.1007/978-94-015-9900-9.
[40] A. Kendall, Time-adjusted global warming potentials for LCA and carbon footprints, Int. J. Life Cycle Assess. 17 (2012) 1042–1049, https://doi.org/10.1007/s11367-012-0436-5.
[41] V.P. Shah, R.J. Ries, A characterization model with spatial and temporal resolution for life cycle impact assessment of photochemical precursors in the United States, Int. J. Life Cycle Assess. 14 (2009) 313–327, https://doi.org/10.1007/s11367-009-0084-6.

[42] A. Levasseur, P. Lesage, M. Margni, L. Deschênes, R. Samson, Considering time in LCA: dynamic LCA and its application to global warming impact assessments, Environ. Sci. Technol. 44 (2010) 3169–3174, https://doi.org/10.1021/es9030003.
[43] B. Peuportier, G. Herfray, Evaluation of Electricity Related Impacts Using a Dynamic LCA Model, (2012).
[44] M. Fesanghary, S. Asadi, Z.W. Geem, Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm, Build. Environ. 49 (2012) 245–250, https://doi.org/10.1016/j.buildenv.2011.09.030.
[45] H. Babazadesh, N. Haghighi, S. Asadi, R. Broun, D. Riley, Life cycle assessment of exterior window shadings in residential buildings in different climate zones, Build. Environ. 90 (2015) 168–177, https://doi.org/10.1016/j.buildenv.2015.03.038.
[46] S. Su, X. Li, Y. Zhu, B. Lin, Dynamic LCA Framework for Environmental Impact Assessment of Buildings, Energy Build, 2017, https://doi.org/10.1016/j.enbuild.2017.05.042.
[47] S. Bordebeure, Déchet du Bâtiment, (2017).
[48] L. Tiruta-Barna, Y. Pigné, T. Navarrete Gutiérrez, E. Benetto, Framework and computational tool for the consideration of time dependency in Life Cycle Inventory: proof of concept, J. Clean. Prod. 116 (2016) 198–206, https://doi.org/10.1016/j.jclepro.2015.12.049.
[49] A.H. Shimako, L. Tiruta-Barna, Y. Pigné, E. Benetto, T. Navarrete Gutiérrez, P. Guiraud, A. Ahmadi, Environmental assessment of bioenergy production from microalgae based systems, J. Clean. Prod. 139 (2016) 51–60, https://doi.org/10.1016/j.jclepro.2016.08.003.
[50] A.H. Shimako, L. Tiruta-Barna, A. Ahmadi, Operational integration of time dependent toxicity impact category in dynamic LCA, Sci. Total Environ. 599–600 (2017) 806–819, https://doi.org/10.1016/j.scitotenv.2017.04.211.
[51] A.H. Shimako, L. Tiruta-Barna, A.B. Bisinella de Faria, A. Ahmadi, M. Spérandio, Sensitivity analysis of temporal parameters in a dynamic LCA framework, Sci. Total Environ. 624 (2018) 1250–1262, https://doi.org/10.1016/j.scitotenv.2017.12.220.
[52] IPCC, Climate Change 2013 - the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2013, , https://doi.org/10.1017/CBO9781107415324.
[53] M.Z. Hauschild, M. Huijbregts, O. Jolliet, M. Macleod, M. Margni, D. van de Meent, R.K. Rosenbaum, T.E. McKone, Building a model based on scientific consensus for life cycle impact assessment of chemicals: the search for harmony and parsimony, Environ. Sci. Technol. 42 (2008) 7032–7037, https://doi.org/10.1021/es703145t.
[54] R.K. Rosenbaum, T.M. Bachmann, L.S. Gold, M.A.J. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H.F. Larsen, M. MacLeod, M. Margni, T.E. McKone, J. Payet, M. Schuhmacher, D. van de Meent, M.Z. Hauschild, USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, Int. J. Life Cycle Assess. 13 (2008) 532–546, https://doi.org/10.1007/s11367-008-0038-4.
[55] A. Shimako, Contribution to the Development of a Dynamique Life Cycle Assessment Method, Thesis Report, INSA Toulouse, 2017.
[56] Commissariat général au développement durable, Durée de construction des logements: le rôle des tensions dans l'industire du bâtiment entre 1990 et 2010, (2012).